Noname manuscript No.
(will be inserted by the editor)

Solar surface and atmospheric dynamics

The Photosphere

Martínez Pillet, V.

Received: date / Accepted: date

Abstract Various aspects of the magnetism of the quiet sun are reviewed. The suggestion that a small scale dynamo acting at granular scales generates what we call the quiet sun fields is studied in some detail. Although dynamo action has been proved numerically, it is argued that current simulations are still far from achieving the complexity that might be present on the Sun. We based this statement not so much on the low magnetic Reynolds numbers used in the simulations but, above all, in the smallness of the kinetic Reynolds numbers employed by them. It is argued that the low magnetic Prandtl number at the solar surface may pose unexpected problems for the identification of the observed internetwork fields with dynamo action at granular scales. Some form of turbulent dynamo at bigger (and deeper) scales is favored. The comparison between the internetwork fields observed by Hinode and the magnetism inferred from Hanle measurements are converging towards a similar description. They are both described as randomly oriented, largely transverse fields in the several hecto-Gauss range. These similarities are ever making more natural to assume that they are the same. However, and because of the large voids of magnetic flux observed in the spatial distribution of the internetwork fields, it is argued that they are not likely to be generated by dynamo action in the intergranular lanes. It is concluded that if a dynamo is acting at granular scales, the end product might have not been observed yet at current spatial resolutions and sensitivities with the Zeeman effect. Thus an effort to increase these resolutions and polarimetric sensitivities must be made. New ground- and space-based telescopes are needed. The opportunity offered by the Solar Orbiter mission to observe the Quiet Sun dynamics at the poles is seen as one of the most important tests for confirming the existence, or otherwise, of a granularly driven surface dynamo.

Keywords Quiet Sun magnetism · turbulent dynamo

Instituto de Astrofísica de Canarias
38200, La Laguna, Tenerife, Spain
Tel.: +34-922605237
Fax: +34-922605210
E-mail: vmp@iac.es

1 Introduction

A consensus about the existence of a small-scale dynamo (SSD[1]) operating at the solar photosphere is being consolidated in today's solar physics (see, e.g., Vögler and Schüssler 2007; Abbett 2007; Pietarila Graham et al. 2010; Stein 2012, for a review). High resolution magnetograms from ground and (mostly) space-based telescopes observed in the internetwork are often used to indicate that such a surface dynamo exist (e.g. Danilovic et al. 2010a; Lites 2011). On theoretical grounds, simulations of various kinds have been used to suggest how universal the various ingredients of such a dynamo seems to be (Moll et al. 2011). They all indicate that turbulent shear stresses acting on the inertial range act as the main mechanism able to efficiently convert kinetic into magnetic energy. The conclusions from the various simulations of turbulence in a conducting fluid seems to be that it would have been a lot harder to explain the absence of a surface SSD than its presence. With an emphasis on the observational side, we review in this work the current status of this consensus and try to pinpoint which aspects are more solidly established and which are less settled.

Section 2 will be the only one that concentrates on simulations and the theoretical aspects related to the problem of the existence of SSDs on the Sun. It will address the most controversial argument questioning the existence of such a mechanism, namely the fact that the solar convective zone has a magnetic Prandtl number that is orders of magnitude smaller than one, while simulations work near the ~ 1 regime most of the time. Low magnetic Prandtl numbers are known to severely discourage dynamo action since the early simulations of convectively driven turbulent dynamos (Nordlund et al. 1992; Schekochihin et al. 2004a, 2005). Recently, progress has been achieved, however, that indicates that an SSD is indeed possible in the low magnetic Prandtl regime (Iskakov et al. 2007; Schekochihin et al. 2007; Brandenburg 2011). But the situation is not conclusive and the papers addressing this issue often resort to the fact that a mixed polarity field is observed at the solar surface as the firmest indication that such a mechanism should exists. However, and in the absence of a clear proof that this observed (internetwork) fields originate from an SSD –and such a proof is not available yet– the only progress to settle this issue will come from further work in the simulation front.

The observational arguments that have been put forward to favor the presence of a solar surface dynamo are discussed later in Section 3. There are basically two such arguments. First, the evidence from the observed Hanle effect in lines such as the SrI 4607 Å line and the careful modeling of these signals indicate the existence of a tangled field with a mean strength of $< B > \sim 130$ G (Trujillo Bueno et al. 2004) some few hundred kilometers above the solar surface (see also Trujillo Bueno et al. 2006, and references therein). This number was originally derived under some model assumptions that made it uncertain to within a factor two. However, a recent study (Shchukina and Trujillo Bueno 2011) of the predicted Hanle signals from the MHD simulations described in Pietarila Graham et al. (2009b) has eliminated some of this model dependency and confirmed such large mean field strengths. As a mixed polarity tangled field at unresolved scales leaves basically no trace in the Zeeman profiles, these fields

[1] Small scale here refers to generation of magnetic fields at scales smaller than the energy injection one, the granulation.

have always been a prime candidate to be considered as originated from a surface SSD. If the tangling occurs at scales near or above present resolutions, some signatures can be detected, though. It is unclear if these fields have been observed using the Zeeman effect (but see Lites et al. 2009; Bellot Rubio and Orozco Suárez 2012, and Section 3). The second observational argument in favor of an SSD comes from the Hinode spectropolarimeter (SP) instrument (Tsuneta et al. 2008; Kosugi et al. 2007) and its unprecedented characterization of the internetwork fields using the Zeeman effect (Lites et al. 2008; Ishikawa and Tsuneta 2011; Orozco Suárez and Bellot Rubio 2012). While transverse fields were known to exist in the quiet sun, as originally found by the Advanced Stokes Polarimeter (ASP; Lites et al. 1996), it was totally unexpected that these fields have a predominant transverse character. This transverse nature seems to fit in a natural way with an origin related to a turbulent dynamo as shown by recent simulations (see Schüssler and Vögler 2008).

A possible outcome given this state of affairs could be as follows. The existence of an SSD acting at granular scales at the solar surface can eventually be confirmed from a set of improved SSDs simulations (along the lines described in Section 2). In them, a continuous distribution of fields is obtained that is able to explain the Hanle depolarization levels from those fields created at the smaller scales and the largely horizontal internetwork fields from those at larger scales. The separation between these two sets of fields does not have to be sharp and a range of spatial scales can contribute to both the Zeeman and Hanle results (or, perhaps, that the two observed processes are due to fields exactly at the same scales as it can be inferred from the recent results of Bellot Rubio and Orozco Suárez 2012). Note that, such a field distribution would solely depend on the existence of the always present turbulent convective motions near the surface and, thus, should be independent of latitude and of activity cycle phase. While this conclusion seems rather plausible given the current evidence, the aim of this work is to address some of the known problems that might prevent such an outcome. In particular, Section 4 describes some observations recently obtained with the IMaX/SUNRISE magnetograph (Martínez Pillet et al. 2011; Solanki et al. 2010) that show regions that display very little magnetic activity, either measured as residual signals in time-averaged deep magnetograms or as evidenced by a lack of flux emergence episodes in the form of small-scale loops (as discovered by Martínez González et al. 2012). It is unclear how these voids are compatible with a granularly driven SSD. That the situation is far from clear has been corroborated recently by the study of (Stenflo 2012, based on SDO/HMI magnetograms) who proposes the existence of a basal flux of order 3 G that is suggested to be an upper limit to the efficiency of an SSD at the solar surface. According to this result all the internetwork fields observed with Hinode/SP will not be generated through such a mechanism and only the Hanle depolarizing fields could be originated through it (if at all).

In spite of this somewhat confusing situation, it is important to stress that our understanding about the nature and the properties of the quiet sun fields has improved enormously in recent years. But it is clear that a number of important questions remains on the theoretical/modelling side and on the observational front. Section 5 finishes this work proposing a way forward to further advance in this understanding of the quiet sun magnetism. Not surprisingly, we promote an effort to increase the polarimetric sensitivity and the spatial and temporal resolutions of both, the Hanle and the Zeeman observations. Studying the statistics of the quiet sun fields at various latitudes will also prove crucial.

2 Small scale dynamo action at low P_m. Implications for the solar case

The seminal reference that triggered the present debate on the existence of a convectively driven turbulent dynamo at the solar surface was the work of Cattaneo (1999), although the debate is older (see, e.g., Petrovay and Szakaly 1993; Lin 1995). It is important to point out that this work mentioned, both, the granular and supergranular scales as possible contributors to such non-helical dynamo. The simulations used closed upper and lower boundaries with vertical fields in both of them. The Reynolds and magnetic Reynolds numbers could be clearly defined for this simulation thanks to the fixed computational grid used to solve the MHD equations. They were $\mathrm{R}e = ul/\nu = 200$ and $\mathrm{R}e_m = ul/\eta = 1000$, with l the characteristic length of the energy injecting convective cells, u the velocity of these cells and ν and η the molecular viscosity and the magnetic diffusivity, respectively. These numbers are large enough to ensure the development of turbulence. But it is important to note that $\mathrm{R}e$ was five times smaller than $\mathrm{R}e_m$ (magnetic Prandtl number of $\mathrm{P}_m = \mathrm{R}e_m/\mathrm{R}e = \nu/\eta = 5 > 1$). Under these circumstances, the magnetic field sees a smooth mean flow efficiently acting on it. The numerical simulation resulted in dynamo action saturating at 20% of the kinetic energy flow. The crucial ingredient was the chaotic nature of the driving flows. Figure 2 of this paper already showed that, at the surface, the strong fields were localized in the downflow lanes, while the cell interiors showed no (vertical) field signature. The situation was different in deeper layers where fluctuating fields were filling basically the whole volume. At the time of the publication, the dominant transverse nature of the internetwork was not known (see Section 3) and this aspect was not analyzed. For this reason, the profiles synthesized by Sánchez Almeida et al. (2003) using these simulations concentrated on the study of the asymmetries induced in the Stokes V profiles (circular polarization) and its comparison with those observed in the internetwork. A shortage of asymmetries indicated that the simulations still did not achieve as much complexity as present in the Sun. However, using this synthesis, and after including effects such as telescope diffraction, it was predicted that when improving the spatial resolution from 1 arcsec to 0.15 arcsec, one should detect four times more Stokes V polarization signals.

A number of assumptions made in this simulation (such as the Boussinesq approximation) have been relaxed in more recent works. The more realistic ones (in terms of their proximity to the physical conditions on the Sun) are those made with the MURaM code (Vögler and Schüssler 2007; Schüssler and Vögler 2008; Pietarila Graham et al. 2010). In particular, they have addressed the important question of the role played by the closed boundary conditions assumed in Cattaneo (1999). Stein et al. (2003) pointed out that, in the solar convective zone, fields are submerged efficiently to the bottom of the convective zone by strong and concentrated downflows showing little recirculation near the surface. This recirculation was artificially enhanced in the simulations of Cattaneo (1999) by the use of closed boundary conditions. Stein et al. (2003) concluded that diverging upflows sweep the fluid into downflows, often vortical, where stretching and twisting becomes effective (and balanced by diffusion) but all these fields are rather rapidly submerged down into the bulk of the convective zone. The energy added to the flux that visits the surface was a very small fraction of the global budget of magnetic energy and the effect cannot be considered a local dynamo. This criticism has, however, been superseded by the MUraM simulations which used an open boundary and

allow for a non-zero pointing flux at the bottom boundary. The way in which this boundary condition was implemented in the simulations of Vögler and Schüssler (2007) was by imposing an artificially increased magnetic diffusivity there. This diffusivity ensured that horizontal fields moving downward in the simulation leave the box unimpeded while, at the same time, prevented horizontal flux from entering the domain. All flux leaving the bottom boundary in these simulations was created by dynamo action inside the box. Vögler and Schüssler (2007) concluded that while the downward pumping of flux outside of the domain does indeed reduce the growth rate of the dynamo, it does not shut it down. They predict that as long as a sufficiently high $\mathrm{R}e_m$ is used (above the critical magnetic Reynolds number, $\mathrm{R}e_m^C$), dynamo action will be observed in the simulations. Specifically, they see exponential growth of the magnetic energy for $\mathrm{R}e_m$ of 2600, while they find a decrease for $\mathrm{R}e_m$ below 1300. Now, here we should caution that the exact values of $\mathrm{R}e_m$ and $\mathrm{R}e$ (and thus of P_m) are not as easily defined as in Cattaneo (1999) simulations. The need to resolve shocks with artificial viscosity schemes or the implementation of the bottom boundary diffusivity necessarily implies that these numbers are more difficult to ascertain. An estimate of the effective Reynolds and Prandtl numbers for the MURaM simulations was given by Pietarila Graham et al. (2010) using various moments of the velocity and magnetic spectra (or Taylor microscales). The various dynamo runs available from this code turn out to have $\mathrm{R}e_m \in [2100, 8300]$ (with the latter value using a grid resolution of 4 km) and $\mathrm{P}_m \in [0.8, 2]$. This set of simulations all displayed an SSD generating magnetic fields inside their volume. The conclusion was that current MURaM simulations (with $\mathrm{P}_m \sim 1$) will show dynamo action as long as $\mathrm{R}e_m > \mathrm{R}e_m^C \sim 2000$. The main mechanism identified for this generation was the stretching and twisting of field lines by fluid motions in the inertial range of the spectrum of velocity fluctuations. In particular, it was concluded that dynamo action is concentrated in the turbulent downflows as field line stretching against magnetic tension is very efficient there (e.g. Stein 2012, for a review). In order to clarify the nature of the observed dynamo action, Moll et al. (2011) have analyzed the underlying physical mechanism under various physical conditions and assumptions. They concluded that for the cases studied (incompressible MHD, Boussinesq convection and compressible solar convection), the field is amplified by similar inertial range shear stresses that are independent of the conditions at the injection scale. The inclusion of compressibility effects or the asymmetry between upflows and downflows generated by the strong stratification did not influence the result. They, thus, termed the dynamo mechanism as universal.

One concern remains about the existence of a possible SSD on the Sun, though. The problem has been known since the early studies of dynamo action in conducting fluids. It was originally formulated by Batchelor (1950) who studied how turbulent motions stretch the field lines and amplify the magnetic energy as long as this process remains unimpeded by ohmic diffusion. Field line stretching is produced by fluid motions in the inertial range whose dissipation scale is set by the viscosity of the fluid. High viscosity ν couples the field lines to the flow and allows it to bend them efficiently. Large magnetic diffusivity η decouples the plasma (and the flows) from the field lines and prevents the bending. Thus, it was always clear that the efficiency of the SSD was going to be controlled by the interplay of these two effects as measured by the ratio $\mathrm{P}_m = \nu/\eta$. Clearly, both conditions $\mathrm{R}e_m \gg 1$ (to favor field line stretching) and $\mathrm{P}_m \gg 1$ (to couple fluid motions and field lines)

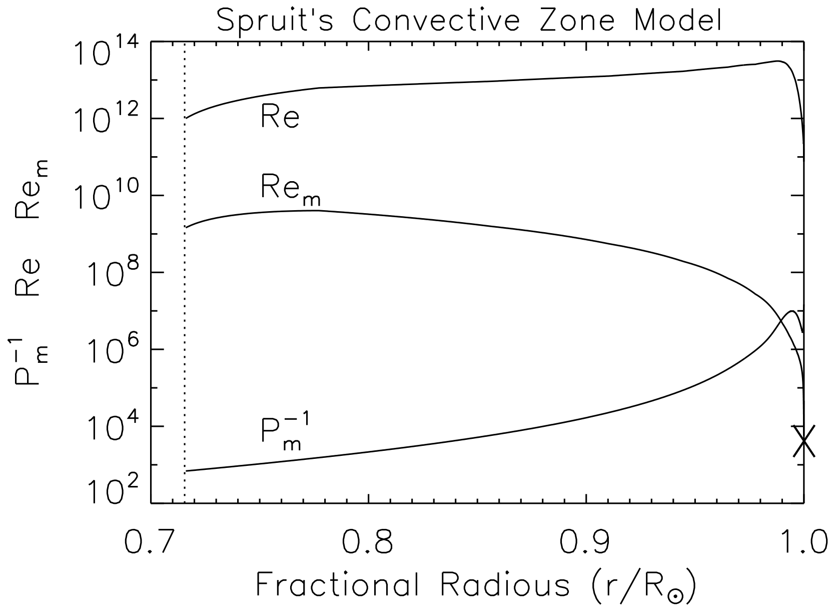

Fig. 1 The Reynolds number, magnetic Reynolds number and (inverse) Prandtl number in the solar convective zone according to the mixing-length model of Spruit (1974). The X near the surface marks the tipical values achieved of both Re and Re_m in the simulations.

boost local dynamo action. Based on an analogy between vorticity and magnetic fields Batchelor (1950) even concluded that for $P_m < 1$ no SSD was possible. This conclusion was later criticized by a number of authors as the analogy cannot include the different initial and boundary conditions seen by these two fields (see, e.g. Boldyrev and Cattaneo 2004). However, simulations in the early 90's (see, e.g., Nordlund et al. 1992), including compressibility and strong stratification, already resulted in dynamo action only for $\mathrm{P}_m \geq 1$ with efficient shutting down of the dynamo for $\mathrm{P}_m < 1$. Other simulations encountering the same problem are discussed in Boldyrev and Cattaneo (2004) and in Schekochihin et al. (2005). Thus, the question of the existence of an SSD at low Prandtl numbers has received some attention in recent years.

Before we briefly describe the results from the numerical studies about the existence of an SSD at low Prandtl numbers, it is important to remember what are the actual numbers that occur in the solar convective zone and get an idea of how far or how close are we from simulating these conditions. To this end, Figure 1 shows Re, Re_m and P_m^{-1} as computed in the mixing-length based model of Spruit (1974). The velocities at the injection scale u are obtained as part of the model and the characteristic length is assumed here to be $l = z/2$, with z the depth inside the convective zone. The magnetic Reynolds number changes from 10^5 at the photosphere to 10^9 at the bottom of the convective zone, whereas the Reynolds number stays constant at a level of 10^{12}. This makes $\mathrm{P}_m \in [10^{-7}, 10^{-3}]$, with the smallest value reached at the photosphere. Thus, everywhere in the Sun, we have

$\mathrm{R}e \gg \mathrm{R}e_m \gg 1$ and $\mathrm{P}_m \ll 1$ which is exactly the regime where the existence of an SSD becomes problematic. It is generally believed that for a sufficiently high Re_m there will always be an SSD at work. But the above mentioned simulations prompted a deeper study about the existence and nature of an SSD under solar conditions. As already mentioned, the simulations by Cattaneo (1999) had $\mathrm{P}_m = 5$ and those from the MURaM code always move close to the $\mathrm{P}_m \sim 1$ case (there is one with $\mathrm{P}_m = 0.8$ that is discussed below). Note that the regime where $\mathrm{R}e_m$ and $\mathrm{R}e$ are similar is actually very favorable for the numerical codes as similar grid sizes resolve the dissipative scales of both, magnetic and velocity fields.

What is the physical argument behind this difficulty to generate an SSD when $\mathrm{P}_m \ll 1$?. Under such conditions the viscous (l_ν) and resistive (l_η) scales follow $l_\eta/l_\nu \sim \mathrm{P}_m^{-3/4} \gg 1$ (Schekochihin et al. 2004a, 2005) and the resistive scale l_η falls in the middle of the inertial range. Turbulent eddies of scales $l > l_\eta$ do the necessary field line bending and twisting for dynamo action at a rate of u_l/l (with u_l the typical flow velocity at this scale). If $\mathrm{P}_m > 1$ only these eddies occur and the field lines always see a spatially smooth flow. However, if $\mathrm{P}_m < 1$ one has now eddies below the resistive scale $l < l_\eta$. These eddies act on the field as a turbulent diffusion with diffusivity $u_l l$ and destroy magnetic energy. It is the predominance of this last process what can make dynamo action impossible as it was seen in the previously mentioned simulations. Using an incompressible spectral MHD code and the PENCIL code [2], Schekochihin et al. (2005) studied what are the possible asymptotic limits when $\mathrm{R}e \gg \mathrm{R}e_m$ and the corresponding values of the $\mathrm{R}e_m^C$ for the existence of a dynamo. The above described effect always translates into a sharp increase in $\mathrm{R}e_m^C$ as $\mathrm{P}_m \to 0$ (see also Pietarila Graham et al. 2009a), but does not prevent the existence of a dynamo in this regime. The two asymptotic limits are, first, as $\mathrm{R}e \to \infty$, $\mathrm{R}e_m^C \to$ const, so that dynamo action is possible for higher $\mathrm{R}e_m$ and, second, $\mathrm{R}e_m^C \to \infty$ with $\mathrm{R}e_m^C/\mathrm{Re} \to \mathrm{P}_m^C$ =const, in which case no dynamo is possible (turbulent diffusion efficiently dissipates magnetic energy at small scales). Which exactly of the two asymptotic limits prevails has been under much debate in recent years. While Schekochihin et al. (2004a) and Schekochihin et al. (2005) (see their Figure 2) favor the existence of a P_m^C (no dynamo) from simulations of incompressible magnetoconvection reaching values of P_m as small as 0.15, Boldyrev and Cattaneo (2004) provided analytical arguments favoring the existence of a $\mathrm{R}e_m^C$.

While the debate in the mid last decade did not look promising for confirming the existence of an SSD at the solar surface, the situation has changed recently (even if not completely settled). Schekochihin et al. (2007) (see also Iskakov et al. 2007) performed simulations of incompressible MHD turbulence reaching values of $\mathrm{P}_m = 0.1$ and with a sufficiently high $\mathrm{R}e_m$ that indicated a plateau region where a $\mathrm{R}e_m^C$ is observed (see their Figure 1b). Admittedly, the number of such simulations proving the existence of this plateau is very small but the authors consider it enough numerical certainty. The results from Brandenburg (2011) using the PENCIL code (that includes compressible effects) and low values of P_m resulted in dynamo action being activated as well. Pietarila Graham et al. (2010) also find growth of magnetic energy in the one case they analyzed with $\mathrm{P}_m = 0.8$. Thus, the most advanced existing numerical simulations of small-scale dynamo action in

[2] See http://www.nordita.dk/software/pencil-code.

turbulent MHD currently favor the occurrence of such a process in the low P_m regime. However, a number of caveats remain:

- First, and most importantly, Re_m^C increases with decreasing P_m. The exact factor depends on the specificities of the simulations. Boldyrev and Cattaneo (2004) suggest a factor 7 increase in Re_m^C when shifting from the $\mathrm{P}_m \gg 1$ to the $\mathrm{P}_m \ll 1$ case. They use an analytical model of isotropic and homogeneous turbulence that includes the extra roughness of the velocity field for $\mathrm{P}_m < 1$. Schekochihin et al. (2007) find from incompressible forced turbulence a factor 3 increase. As in the MURaM simulations one has $\mathrm{Re}_m^C \sim 2000$ (Pietarila Graham et al. 2010), this means that as soon as we move into the low-P_m regime, we need magnetic Reynolds numbers above at least 6000 to be able to trigger dynamo action. These magnetic Reynolds numbers are not currently achieved by this code. In particular, none of the runs used by Danilovic et al. (2010a) would be able to actually sustain dynamo action. On top of that, the saturated field strength is known to decrease with decreasing P_m, thus the expected field strengths will be smaller than those computed for $\mathrm{P}_m \sim 1$. The exact amount of this reduction is still a very controversial issue (see Schekochihin et al. 2004a, 2007; Brandenburg 2011) and its magnitude for the solar case unknown. But the net effect will be a reduction in the fields as compared to those computed for $\mathrm{P}_m > 1$.
- To complete the demonstration of the existence of a dynamo driven by fluid motions in the inertial range at low P_m values, a growth rate of the dynamo scaling with $\mathrm{Re}_m^{1/2}$ must be obtained from the simulations. Neither Schekochihin et al. (2007) nor Pietarila Graham et al. (2010) have reached that (see Figure 3 of the latter work). Simulations with an increased resolution are needed to finally settle this issue. Schekochihin et al. (2007) concludes that, as long as this is not achieved, the mechanism that sustains the growth of the magnetic field fluctuations in the low-P_m regime will remain basically *unknown*.
- Schekochihin et al. (2007) and Iskakov et al. (2007) concluded that in the $\mathrm{P}_m \ll 1$ regime, the magnetic energy spectra is fundamentally different from that found in the $\mathrm{P}_m \gg 1$. The spatial distribution of the growing magnetic fields is qualitatively different too (see Figure 2 in Schekochihin et al. 2007). This indicates that the use of simulations in the $\mathrm{P}_m \sim 1$ range to compute the ensuing Stokes profiles and its comparison with those observed may not be justified.
- The often simulated case with $\mathrm{P}_m \sim 1$ has the same spectral energy properties and field distribution as the $\mathrm{P}_m \gg 1$ case (Schekochihin et al. 2004b). This is probably why the case with $\mathrm{P}_m = 0.8$ simulated by Pietarila Graham et al. (2010) was so similar to the those in the range of $\mathrm{P}_m \in [1, 2]$.

Let us finalize this section by stressing that if the situation looks confusing, it is because this has indeed been the case in this topic for some time (see Iskakov et al. 2007; Schekochihin et al. 2007, who speak about a frustrating outcome). One argument commonly given to promote the existence of an SSD is the observation of a mixed polarity field in the internetwork regions of the Sun (and many of the above mentioned works use this argument one way or another). Figure 2 of, both, Cattaneo (1999) and Vögler and Schüssler (2007) clearly indicate that this is a reasonable argument. The point we want to stress here is that the same applies to Figure 10 from Stein and Nordlund (2006), which *does not* include an SSD. Pietarila Graham et al. (2009a) estimate for this simulation a $\mathrm{Re}_m \sim 600$, which

is known to be too small to develop dynamo action. However, their mixed polarity distribution located in the interganular lines looks as 'solar' as in the other cases. In the work of Stein and Nordlund (2006) emphasis is made on diverging upflows bringing flux to the surface, expulsion to the intergranular lanes and sweeping of field lines into strong downflows that carry the flux into deeper layers. These simulations extent typically further down than those that concentrate in SSD generation and also include larger scales such as those associated with the meso-granulation. As shown in Fig. 1, the deeper we move into the Sun, the larger $\mathrm{R}e_m$ and P_m (although still smaller than one). Thus, a valid question is if it is not more natural to ask if a solar SSD exists at meso- and supergranular scales and, if so, whether they dominate over that that might exists at granular ones. This point will be further discussed in Section 4.

3 Observed signatures of small scale dynamo action at the solar surface

We now turn to the observational aspect of the discussion and ask the question: Have we seen the fields produced by a possible SSD operating at the solar surface? As it will become evident, there has been, as before, solid observational progress and areas with much confusion. Basically, two candidates exist that are often considered as by-products of an SSD, the internetwork fields and the, so-called, hidden fields that generate the Hanle depolarization signatures.

3.1 Zeeman signals

There is no question that Hinode/SP data has produced a major quantitative and qualitative jump forward in our understanding of the internetwork fields. The publication by Lites et al. (2008) of a gigantic slit scanned map with consistent 10^{-3} polarimetric sensitivity and homogeneous spatial resolution of 0.3 arcsec changed our view of the quiet sun magnetism. In this map, a myriad of patches with predominant linear polarization signatures was discovered. The ASP already found the existence of episodic burst of largely transverse fields (the Horizontal Internetwork Features, HIF, Lites et al. 1996) but they were thought to be rather sporadic. The only previous indication of their existence and global character came from the SOLIS instrument as found by Harvey et al. (2007). But no prediction from the simulations or estimate of their magnitude was available. The existence of this ubiquitous horizontal field has now received full confirmation from the SUNRISE/IMaX data (Danilovic et al. 2010b) who could make the first study of their evolution (see the animation in Solanki et al. 2010) and establish a solid statistics of their lifetimes. Both instruments, Hinode/SP and SUNRISE/IMaX coincide in locating these HIF at the borders of the upflowing granules for a large fraction of their evolution. Lites et al. (2008) emphasized that the linear polarization signatures were not co-spatial with line-of-sight fields that were more frequently found in the intergranular lanes.

Before the publication of Lites et al. (2008) most of the discussion on the internetwork flux concentrated on obtaining its mean unsigned flux (see Solanki 2009, for a review on this topic previous to the impact of the Hinode measurements). The idea was that an intricately complex field with mixed polarities observed

in the best available Stokes V magnetograms was the outstanding description of the internetwork fields. Increased resolution (or sensitivity) will result into ever increasing amounts of longitudinal signals observed as there was less and less cancellation due to instrumental effects. Either because of lack of reliable measurements of the field inclination or because of a habit to focus studies of solar magnetism exclusively in longitudinal magnetograms, no mention to its possible transverse character was traditionally made. As the field strengths were expected to be near or below equipartition values (less than 500 G, see Keller et al. 1994), these fields were not thought to be necessarily vertical either. Before the Hinode results, measurements of $<|B_L|>$ (the spatially averaged unsigned longitudinal flux in the internetwork) were routinely being made and its variation with the spatial resolution closely followed (Sánchez Almeida et al. 2003). In a way, Hinode/SP results have made this emphasis obsolete. We now know that these fields are largely transverse and one should mainly care about $<|B_T|>$ or simply about the spatially averaged $<|B|>$. We should caution here that these magnitudes are obtained by observations of different Stokes parameters that have different sensitivities to the real magnetic field components on the Sun and to the fraction of the observed pixel that they occupy (the filling factor). Thus, the steps to compute $<|B|>$ from the observed $<|B_L|>$ and $<|B_T|>$ are more problematic than what one might anticipate. Lites et al. (2008) estimated that the quiet sun map obtained by Hinode/SP had a $<|B_L^{app}|>$ of 11 G (or Mx cm^{-2}) and a $<|B_T^{app}|>$ of 55 G. These estimates were based on using integrals of the Stokes parameters that were calibrated against magnetic fluxes but with no account for the fraction of the pixel occupied by the fields. This is why they are named 'apparent' fluxes. An analysis performed by Orozco Suárez et al. (2007) of the same data, but this time using a Milne-Eddington (M-E) inversion code including a filling factor as a free parameter, resulted also in a predominantly transverse nature of the internetwork, albeit with a smaller ratio of transverse to longitudinal apparent fluxes.

It is no exaggeration to say that the ratio measured by Lites et al. (2008) $<|B_T^{app}|>/<|B_L^{app}|>\sim 5$ came as a surprise and was, thus, subjected to a deep scrutiny by the community.

Several factors can create a systematic bias in this ratio. Spatially averaging noise affects a positively defined quantity such as B_T in a way different than what it does to a signed quantity (B_L). As the Zeeman effect has a sensitivity different for each of these two components, the visibility of a given field strength is different depending on whether it is a field aligned with the LOS or perpendicular to it. In particular, fields close to the noise levels translate into different visibility thresholds. Last but not least, there is the already mentioned difference in how the filling factor couples to the real field strengths and inclinations for each one of the two components and depending on the specific method of analysis used. These effects and their impact into the factor 5 obtained by the first Hinode/SP measurements have been studied by various authors (Asensio Ramos 2009; Borrero and Kobel 2011; Stenflo 2011; Sánchez Almeida and Martínez González 2011; Steiner and Rezaei 2012, see the latter for a review). It all translates into understanding how exactly noise influences the final result given the method of analysis one follows and the various thresholds for inclusion of a given pixel or not. Depending on the specific case, different values for $<|B_T^{app}|>$, $<|B_L^{app}|>$, or inverted parameters B, inclination, azimuth and filling factor are obtained. Figure 2 shows the central portion of the same magnetogram used in Lites et al.

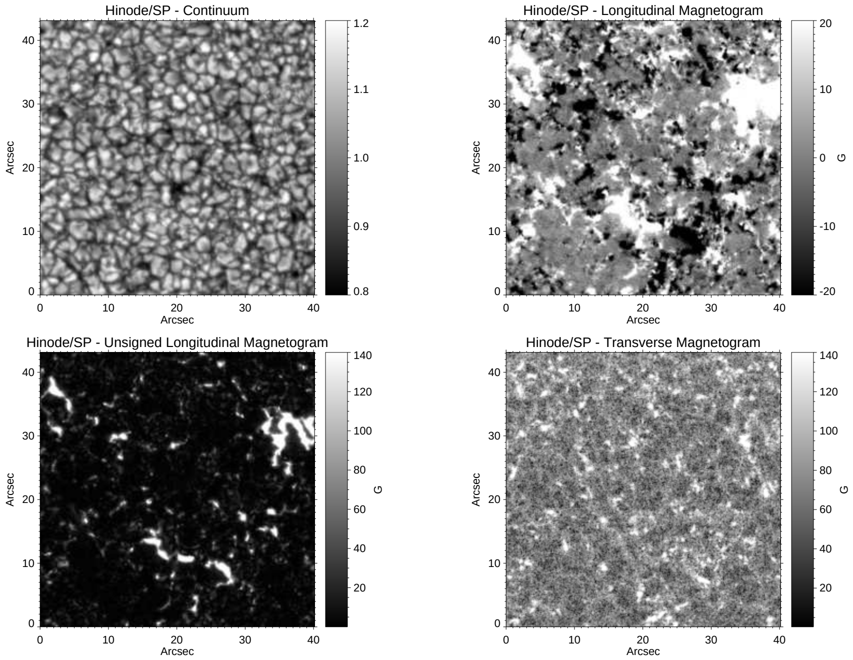

Fig. 2 Continuum intensity from the central portion of the Lites et al. (2008) Hinode/SP map (top left), signed magnetogram from the same portion (top right), unsigned magnetogram (bottom left) and transverse magnetogram (bottom right).

(2008) with the top panels displaying the continuum intensity and B_L^{app} scaled to ±20G. Network bright points are visible (e.g., top-right of the Figure) and the corresponding large Stokes V signals evident in the magnetogram. The bottom two images provided $|B_L^{app}|$ (left) and $|B_T^{app}|$ (right) both scaled within *the same range* [0,140]G. Almost all of the signals seen in the left image are identified with network regions as can be recognized by inspection with the two top panels. Thus, they will be excluded when computing $< |B_L^{app}| >$ for internetwork regions. In contrast, all of the signals seen in the right panel correspond to internetwork and contribute to the $< |B_T^{app}| >$ average. But note also in this last panel that regions with no apparent signals do not show up as dark black as in the unsigned longitudinal image, but they show a grey shade. This background is created by noise and it is larger than for the longitudinal magnetogram simply because of the effects described above. These regions should neither be just included when computing $< |B_T^{app}| >$ nor completely excluded (as some transverse fields might exist there). It is in all of these details that reside some of the contradictory numbers that have been published. The most promising venue to clarify the situation is that of reducing noise. With the current instrumentation this can only be done by using longer integrations. This strategy has been recently pursued very successfully by Orozco Suárez and Bellot Rubio (2012) and Bellot Rubio and Orozco Suárez (2012). They use slit integrations of 6.1 minutes that reach a polarimetric sensitivity close to 10^{-4}, one order of magnitude better than commonly achieved. For visible lines, this improvement lowers down the detectability threshold for average

transverse fields by a factor 2-3. Bellot Rubio and Orozco Suárez (2012) show that slit positions with almost 10 minute effective integration time that harbor linear polarization signals basically everywhere (60% above 4.5σ).

The increased exposure times impose a penalty in the sense that the spatial resolution is decreased and evolutionary effects are intermingled in the final results.

This should not give the impression that these signals are always present on the Sun and detectable if sufficient sensitivity is available as they might have occurred in these pixels for only a fraction of the exposing time. Nevertheless, the data obtained with these long exposures is perfectly suited to reduced the noise induced bias present in the previous analysis of Hinode/SP. The M-E inversions performed by Orozco Suárez and Bellot Rubio (2012) and Bellot Rubio and Orozco Suárez (2012), consistently show that the internetwork fields have intrinsic field strength typically in the range of 100-200 G with basically no kG present, a strongly peaked field inclination distribution near 90^o, with most of the pixels displaying inclinations in the range $[45^o, 135^o]$, and an azimuth with no preferred orientation. Filling factors move in the range of [0.2,0.4]. The authors inverted only those pixels that had a sufficiently large linear polarization signal (in either Stokes Q and/or U) to ensure a reliable result from the inversion. These results are largely free from most of the concerns expressed so far on the nature of internetwork fields. One criticism that remains to this analysis is the use of the M-E approximation and inversions able to reproduce the asymmetries are desirable. But the main conclusions from these recent analysis are likely to be confirmed by these more complex inversions, as those based in the M-E approximation are known to provide robust atmospheric means even in the presence of complex stratifications (see Westendorp Plaza et al. 1998). Thus internetwork fields do not have an isotropic distribution of inclination as it has been argued in a number of recent works (Asensio Ramos 2009; Stenflo 2011; Sánchez Almeida and Martínez González 2011) and their field strengths are typically on the few hG range.

Inversion codes allow an inference of the filling factor as a separate free parameter (admittedly, the most model dependent of all of them). Thus Orozco Suárez and Bellot Rubio (2012) were able to give real mean (not apparent) fluxes. For the real fluxes, they obtained, $< |B_T| >\sim 198$G, $< |B_L| >\sim 64$G and $< |B| >\sim 220$G (here the $<>$ average means those pixels with large enough Stokes Q and U signals to allow a proper inversion, not the complete map). Their ratio, now, is $< |B_T| > / < |B_L| >\sim 3.1$. Note that because this ratio has eliminated filling factor effects and the inclusion of only those points that were inverted, it is not directly comparable to the number provided by Lites et al. (2008). However, it confirms the largely transverse nature of the internetwork fields as originally shown in that work. By eliminating filling factor effects, this new ratio allows for a cleaner comparison with numerical simulations.

Interestingly, although not anticipated, numerical simulations of magnetoconvection seem to have no problem in generating large amounts of horizontal fields. Soon after the publication of the results from Hinode, the SSDs simulations from Schüssler and Vögler (2008) (MURaM code) and those from Steiner et al. (2008) explained that these large amounts of transverse fields were present in their simulation boxes at different heights. The simulations from Steiner et al. (2008) were not dynamo simulations and used instead imposed fields in both vertical and horizontal directions. These two initial conditions generated a predominant horizontal field in the region where the FeI line pair observed by Hinode forms. Thus, while

SSDs are capable of generating a dominantly transverse field, it is not an exclusive property of them. In the work of Steiner et al. (2008), it was through the well known flux expulsion mechanism of vertical fields to the intergranular lanes that horizontal field lines were expelled above the granules in the overshooting region, generating the predominant transverse fields. The quantitative comparison with the observed fields was more complicated and both simulations fell short of the values observed. Danilovic et al. (2010a) used the MURaM simulations and performed spectral synthesis including instrument degradation and noise to compare the values predicted from the simulations with those observed by (Lites et al. 2008). The result was that while the factor five in the ratio of apparent mean fluxes came naturally out of the SSD simulations, the absolute flux levels were close to those observed only if the SSD fields were multiplied artificially be a factor 2-3. After this artificial increase, the average values in the SSD simulation are closer to 100 G in the formation region of the FeI lines which is nicely compatible with the peak field strength in Orozco Suárez and Bellot Rubio (2012). Similarly, the simulations presented by Steiner et al. (2008) resulted in average fields of the order of 20 G for the transverse component and suffer from the same problem as the SSD simulation. One could argue that the small $\mathrm{R}e_m$ numbers achieved in the SSD simulations and the field strength introduced in the simulations were too low and simply increasing them will explain the higher fluxes encountered by the observations. In any case, what was clearly established from all these studies was the fact that the natural state of a magnetic field component below equipartition strengths and closely coupled with the solar granulation is that of a predominant transverse field component as found by Hinode/SP. Another conclusion is that while SSDs are compatible with this result, the latter cannot be offered as a demonstration of their existence at the solar surface as a non-dynamo magnetoconvective simulation found the same results.

Another attempt to investigate whether the internetwork fields are generated by dynamo action has been presented recently by Lites (2011). In this work, the polarity imbalance of the internetwork field regions in 45 Hinode/SP maps is studied. Arguably, polarity balance is considered a necessary outcome of an SSD. However, and as stated by Lites (2011), this is not a sufficient condition as after a sufficiently large number of turnover times, the same polarity balance is to be expected in non-dynamo simulations. The difficulty here stems from the fact that to measure the internetwork polarity imbalance one needs to carefully isolate these fields from network ones. If the internetwork fields originate somehow by the shredding of nearby network fields, one expects the internetwork to have the same sign of the imbalance and a proportionality between the two. Interestingly enough, while no scaling with the unsigned flux was found, a suggestive correlation between the signed flux imbalance in the internetwork and that in the nearby network was measured (see Figure 3 of the paper). However, being conclusive with this result is difficult as the isolation between internetwork and network fields is always problematic. This approach deserves further study, probably including some stray-light correction that deconvolves the wings of the spread function. This would allow to decontaminate the internetwork fields from the surrounding network contribution and allow a more reliable study of the resulting polarity imbalances.

It is clear that it will be very difficult to conclusively demonstrate that the hG, predominantly transverse internetwork fields originate from a granulation driven SSD. As mentioned in the above paragraph, we can only aim at disproving the

SSD hypothesis rather than expect a firm confirmation of its presence. In Section 4, we present a recent result that, if consolidated, could be considered as one such refutation.

3.2 Hanle signals

Scattering polarization in spectral lines and its modification via the Hanle effect allows to study a completely different parameter space of solar magnetism not accessible with the Zeeman effect (see the reviews in Trujillo Bueno et al. 2006; de Wijn et al. 2009; Stenflo 2011). A tangled field distribution within the resolution element is invisible through the Zeeman effect but can leave a clear imprint in the linear polarization profiles as long as the field strengths are below the Hanle saturation values (typically, a few hundred Gauss). While strong homogeneous vertical fields are hardly hidden in Stokes V through the Zeeman effect, weak disorganized transverse fields show up easily in Stokes Q and U of selected spectral lines thanks to the Hanle effect. This different sensitivity of Hanle effect has provided recently (Trujillo Bueno 2011) a seemingly alternative description of the Quiet Sun fields to that discussed above (and inferred from the Zeeman effect). Ever since the early studies (Stenflo 1982), the Hanle signals have been interpreted as being due to a tangled mixed polarity field. For this reason, it has always been natural to associate these fields with the outcome of a turbulent dynamo (see, e.g. Vögler and Schüssler 2007; Pietarila Graham et al. 2010) This alternative description can be summarized as follows. The center-to-limb variation of the depolarization signals observed in the optically thick SrI 4607 Å line suggests the presence of a tangled field with characteristics strengths of $B \sim< 130 >$ G (as mentioned in the Introduction). This value is computed using realistic atmospheric models of the solar surface and complex 3D radiative transfer calculations(Trujillo Bueno et al. 2004; Shchukina and Trujillo Bueno 2011). In contrast, the analysis of the depolarization signals of a set of optically thin molecular lines suggests a mean field of the order of only $< 10 >$ G (Trujillo Bueno et al. 2004; Kleint et al. 2011). These two distinct fields can be made compatible if one realizes that the molecular lines are entirely formed in the hot smooth upflowing granules and that these lines are blind to the fields present in the turbulent intergranular lanes (Trujillo Bueno et al. 2004). The SrI line however sees the fields in both regions and, in order to give rise to average values of 130 G over the whole solar surface, Trujillo Bueno et al. (2004) concluded that one must have $< B > \gtrsim 200$ G (very close to the Hanle saturation regime for this line) inside the lanes. This intergranular fields would generate most of the SrI depolarization while having no effect in the linear polarization signals from the molecular lines. It is interesting to point out that when the SrI depolarization levels are computed with the MURaM SSD simulations, Shchukina and Trujillo Bueno (2011) find that the depolarization levels are far too low. This is not surprising as these SSD simulations reach fields of the order of 20-30 G, very far from the typical 130 G that is needed. The only way in which an agreement with the observed depolarization values could be achieved was by multiplying everywhere the field strengths in the simulations by a factor 12. This factor is four times larger than that needed by Danilovic et al. (2010a) to match the observed apparent mean Zeeman fluxes of Hinode/SP with those in the MURaM simulations.

This description of the quiet sun fields as inferred from the Hanle signals is generally accepted and no clear alternative exist. However, it is clear that one would like to see it confirmed by an analysis that is less model dependent (see Kleint et al. 2011; Stenflo 2012, who point out that the analysis made using molecular lines is differential in contrast to that made with the atomic lines). The fact that the SrI line is so close to the saturation regime has also brought some criticism of the actual interpretation of the observed depolarization levels (Sánchez Almeida 2005). Indeed, very little variation of the SrI polarization signals has been detected and this can be used to argue that the tangled hidden field is independent of the solar cycle, favoring an origin related to SSD action (Trujillo Bueno et al. 2004; Vögler and Schüssler 2007; Pietarila Graham et al. 2010). One other explanation, of course, could be that the signals in the intergranular lanes change with the activity cycle but we do not see the effect because they are always in the Hanle saturation regime.

In any case, the existence of this turbulent unresolved field is well established and one would like to understand if it bears any relation with the internetwork fields observed by Hinode/SP and described before. Note that when we say unresolved here, we refer to the Hanle observations used in the analysis that were obtained over large spatial scales (several arcseconds) and with exposure times of the order of one minute or so. Taken at face value, what the Hanle measurements need are small scale (arcsecond scale or below) non-vertical field patches (the Hanle effect is insensitive to vertical fields), with field strengths below equipartition with granulation ($\sim$ 400 G). It is evident that these are the properties of the internetwork fields described by Bellot Rubio and Orozco Suárez (2012) and Orozco Suárez and Bellot Rubio (2012) and one is tempted to conclude that the Hinode/SP fields are also the fields corresponding to the Hanle signals. Bellot Rubio and Orozco Suárez (2012) specifically mentions this possibility. One would be tempted to go further and state that it would be rather strange to have the Sun harboring two families of fields with so many things in common but that are totally unrelated. Thus, we also favor here the identification of the Hinode/SP internetwork fields with those that produce the Hanle depolarization signals (see also Lites et al. 2009). Perhaps, the only difficulty we encounter with this identification is the well known fact that the HIFs (the internetwork transverse fields) have a clear preference to be located at the borders of granules (Lites et al. 2008; Danilovic et al. 2010b) not in the intergranular lanes as required by the SrI depolarization measurements. However, this could be a minor problem as a granular border might be sufficiently close to what is needed. An evident way to test this identification would be to invert a volume of the Hinode/SP internetwork observations with an inversion code that provides the complete atmospheric stratification such as the SIR code (Ruiz Cobo and del Toro Iniesta 1992). Then, perform the Hanle synthesis as in Trujillo Bueno et al. (2004) and Kleint et al. (2011) for the atomic and molecular lines and compare the result with the observations. In this exercise some assumptions about the upper layers might be needed to extend the retrieved atmospheres over the range of formation of SrI line, but such an extension can be reasonably done.

In any event, it is clear that spatially resolved Hanle depolarization measurements (Stenflo 2012) that tell us where exactly the SrI depolarization signals occur in the Sun are urgent.

4 Deep magnetograms and 'dead' calm areas: implications

As commented in Section 1, dynamo action concentrates in the turbulent downflows as field line stretching and amplification is more efficient there. A dramatic visualization of this can be seen in Figure 1 of Schüssler and Vögler (2008). Basically all of the intergranular lanes are seen to participate in this dynamo swing. One can then expect that the observable effects of an SSD driven by the granulation would be distributed homogeneously over spatial scales similar to that of the granulation after a period of time long compared with the lifetime of an intergranular lane (which is similar to that of the granules themselves, 10 minutes, cf. Title et al. 1989). In particular, the internetwork fields seen by Hinode/SP must be uniformly distributed over granulation scales. Thus, if we are able to somehow make a statistics of the location of these fields, the inferred spatial distribution must reflect the spatial scale of the granulation and have no voids larger than the typical size of one granule (or at least, the probability of occurrence of such voids will be small, see below). On the contrary, if one finds areas on the quiet sun where many intergranular lanes have existed but none of the expected effects of a presumed granular SSD are seen, one can conclude that no such SSD has been detected.

While snapshots from SSDs have been used to make spectral synthesis including the degradation effects of telescopes and detectors (Danilovic et al. 2010a; Shchukina and Trujillo Bueno 2011), what one needs is a complete time series that allows the study of the generation and disappearance of the dynamo fields at current spatial resolutions and polarimetric sensitivities. This study is unfortunately not available yet. From an observational perspective, we have seen how internetwork fields evolve at the solar surface with unprecedented detail. Both Hinode/SP and SUNRISE/IMaX have convincingly shown that internetwork fields are fed into the surface in the form of emerging small scale loops (rather than in the form of, for example, spontaneous appearances of newly created flux patches in the intergranular lanes). Hinode/SP with its superior spectral resolution and coverage has allowed to study a large number of such events (see Centeno et al. 2007; Martínez González and Bellot Rubio 2009; Ishikawa et al. 2010; Viticchié 2012; Gömöry et al. 2010, the latter for ground observations in the infrared) with great detail. Basically a horizontal patch is first detected in linear polarization that later displays two opposite polarity footpoints that move apart. The distance between the footpoints of these small scale loops is typically 1 Mm, the lifetime 10 minutes and the magnetic flux of around 10^{17} Mx (see the statistic in Martínez González and Bellot Rubio 2009). Danilovic et al. (2010b), using data from SUNRISE/IMaX, identified a large number (thousands) of HIFs that they associate with flux emergence in the form of loops. Such a large amount of occurrences emphasize this process as the main source for internetwork flux at present resolutions and sensitivities. A case in point is that described by Guglielmino et al. (2012) who analyzes in detail what is probably the largest quiet sun loop ever observed. In this case, a maximum footpoint separation of 4.5 Mm is achieved with a magnetic flux content of 6 10^{17} Mx and a duration of 25 minutes. This quiet sun bipole, that has one order of magnitude less flux than the smallest ephemeral region studied by Hagenaar et al. (2003), is arguably not generated by any process that occurs at granular scales. It is known that dynamo simulations generate similar loop-like structures (as the horizontal fields described in Section 2 are part

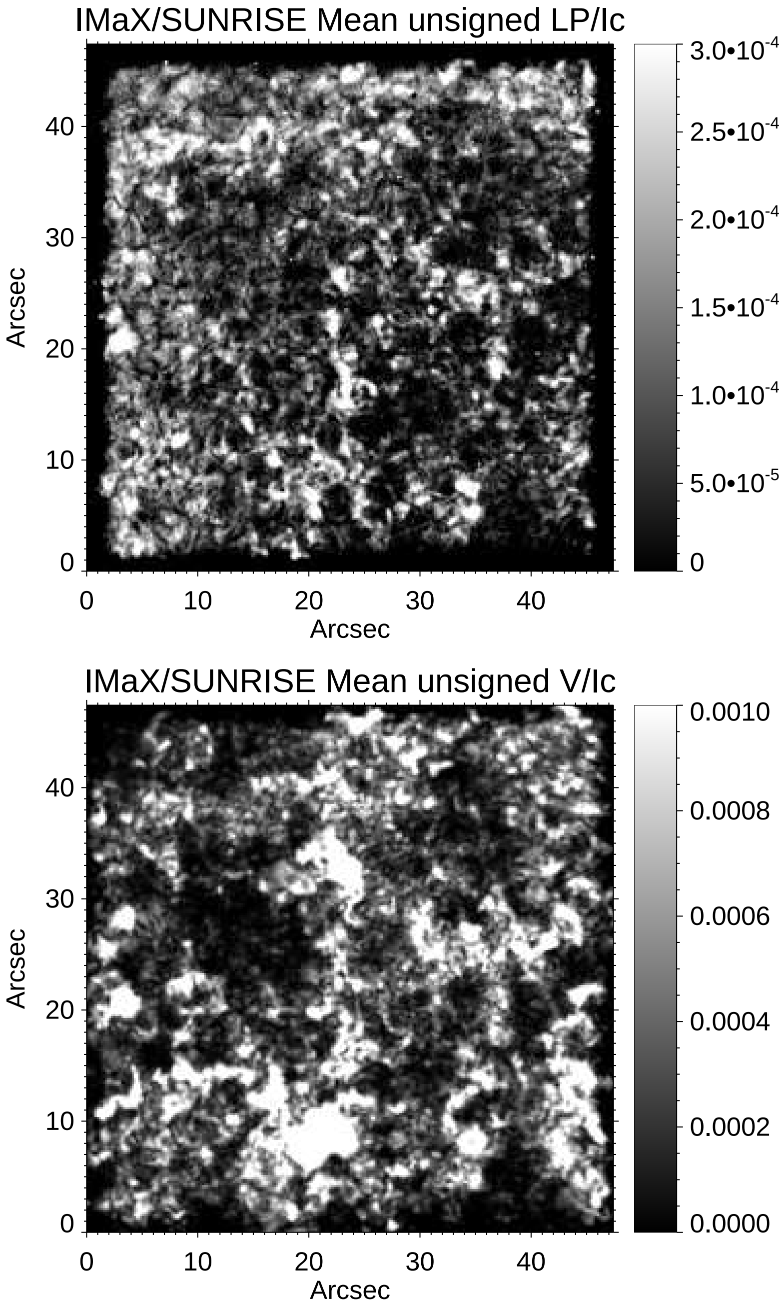

Fig. 3 SUNRISE/IMaX deep linear polarization magnetogram integrated over a 30 minute period (top). SUNRISE/IMaX deep circular polarization magnetogram integrated over the same period (bottom). Both are computed according to the definitions in Eq. 1.

of them). But a comparative study of the maximum footpoint separation, flux content, etc., is missing.

A recent study about loop emergence in the quiet sun has recently been published that is relevant for our discussion. Using the two time series of the first flight day obtained with the IMaX instrument, Martínez González et al. (2012) studied the emergence of 497 magnetic loops identified in them. They estimate an event rate of 0.25 loop h^{-1} arcsec^{-2}. If we associate a typical linear size of 2 arcsec for a granule and a lifetime of 10 minutes, this rate can be translated into 0.17 loops per granule (it takes 6 granules to get one quiet sun loop). Each one of these time series lasted for about 30 minutes, so granulation was efficiently created and destroyed over their timespan. Such a large number of detected loops allowed them to study the spatial distribution of these magnetic flux emergence processes. The result they obtained was that the spatial distribution of loop events was far from homogeneous at granular scales. They found what they termed "dead calm" areas where simply no loop was seen to emerge during the time series. One could argue that these calm areas can be created by chance and that their existence is simply a mere coincidence. However, the authors perform a statistical study of the likelihood of such voids given their size (70-100 arcsec^2) under the assumption of a spatially uniform loop emergence probability. They modeled the probability of finding one such large circular void with a resulting estimate of 3×10^{-4}. Two such dead calm areas were cleanly identified.

Let us show from another perspective how unlikely this result is. In voids of this size, one can fit around 20 typical granules at any given time. As the time series covered 3 granular lifetimes, 60 granules existed inside them which would have given rise to at least 10 loops at the above rate of creation, but none was found. And it occurred in two unrelated regions. How is it possible that if magnetic loop emergence is the observable outcome of SSD action, one encounters regions where this is not activated? While we find this result highly incompatible with the existence of a granularly driven SSD, we need a solid comparison with simulations including all of the possible observational biases to provide a firm answer.

We must note that a non-uniform distribution of quiet sun fields has been known for some time. They were identified by (Lites et al. 2008, and references therein), who pointed out the existence of mesogranular scale voids in the Hinode/SP map. The preference of internetwork fields to be located at mesogranular scales has been clearly demonstrated using the same SUNRISE/IMaX data as that used to identify the voids (see Yelles Chaouche et al. 2011), but note that these voids were much larger than a mesogranule and have a scale closer to that of a small supergranule (see, e.g. Meunier et al. 2007, who give radius in the range of 8 to 30 arcsec).

One could argue that whereas no loop emerged in these dead calm areas, they were probably not devoid of some subtle form of internetwork field presence. However, inspection of the IMaX data with a scaling close to the noise levels readily shows that the locations of these voids clearly harbored less activity than the rest of the observed area. To prove this point more clearly, we produced two time averages of the IMaX time series that are shown in Fig. 3. The two quantities that are displayed correspond to deep magnetograms computed as:

$$\overline{LP} = \frac{1}{N}\sum_{i=1}^{N}\Big(\frac{\sqrt{Q_i^2+U_i^2}}{I_c} - \epsilon_{LP}\Big) \qquad \overline{V} = \frac{1}{N}\sum_{i=1}^{N}\Big(\frac{|V_i|}{I_c} - \epsilon_{V}\Big) \tag{1}$$

where ϵ_V and ϵ_{LP} are quantities inferred from the data that allow convenient reduction of the noise when doing the time averages of the otherwise positively defined quantities. The deep magnetograms in Fig. 3 evidence the same two voids as detected by Martínez González et al. (2012). They are centred at coordinates [15,25] and [35,37]. The voids are visible in both the linear and the circular polarization deep magnetograms. Note that the scaling of both magnetograms saturates at 3×10^{-4} for $\overline{LP}$ and at 10^{-3} for $\overline{V}$. The calibration constants published by Martínez Pillet et al. (2011) would have translated these values into 45 and 5 G respectively. Measurements below these fluxes are at the limit of state of the art imaging magnetographs. These deep magnetograms show that they had reduced levels of magnetic activity and it is correct to refer to them as magnetically calm (maybe, not dead). The question, of course, is what was special about the many intergranular lanes that populated these regions that prevented them from displaying the magnetic activity levels seen elsewhere.

5 Where do we go from here?: higher sensitivities and higher latitudes

The simulations described in Section 1 have reached $\mathrm{R}e_m \in [5000, 8000]$ (Pietarila Graham et al. 2009b). However, they fail to provide the magnetization levels needed to explain, both, the Hanle depolarization signals of the SrI line and the Hinode/SP fluxes (see Danilovic et al. 2010a; Shchukina and Trujillo Bueno 2011; Orozco Suárez and Bellot Rubio 2012). This is often explained arguing that the simulations are still far from the magnetic Reynolds numbers of the Sun. But the values that are achieved by them are *only* about one order of magnitude below the expected values at the solar surface. In contrast, they reach, at best, similar $\mathrm{R}e$ values, which are 10^7 times smaller than what we encounter on the Sun (see Fig. 1, where the values achieved by the simulations are marked by an X near the surface). There are about 5 orders of magnitudes in the inertial range below the resistive scale, l_η, populated with cells that generate an enhanced turbulent diffusion that are not present in the simulations. As mentioned in Section 1, recent numerical simulations show that this might not be a problem to obtain dynamo action in the low P_m regime. But they also tell us that the value of the critical magnetic Reynolds number needed $\mathrm{R}e_m^C$ to sustain dynamo action increases sharply when $\mathrm{P}_m < 1$. A factor 3-7 increase in the value of $\mathrm{R}e_m^C$ is expected. As in the MURaM simulations this number is ~ 2000, we expect this code to display a dynamo only when $\mathrm{R}e_m > 6000$ or larger as soon as they use Prandtl numbers in the right ballpark of the problem. Let us see the implications for some of the inferences that are made using the available numerical simulations. In the case of the MURaM runs, Danilovic et al. (2010a) found a plausible scaling of the saturated field strengths with $\sim \mathrm{R}e_m^{1/2}$. Their run G with $\mathrm{R}e_m \sim 5200$ has a mean field of 30 G (at $\log\tau \approx -1$). If we scale it to a solar value of $\mathrm{R}e_m \sim 10^5$ following this square root scaling, we obtain 130 G. This is the value needed to explain the Hanle depolarization measurements of the SrI line (and the most probable field strength found in the internetwork by Orozco Suárez and Bellot Rubio 2012). This nice agreement was already pointed out by Shchukina and Trujillo Bueno (2011). However, for the reasons explained above, this is probably a mere coincidence. If this simulation would have been done with the same $\mathrm{R}e_m$ but with P_m of, say 0.1 (as in the simulations proving dynamo action at low Prandtl numbers), no dynamo action would have been found. The

field strength to introduce in the above scaling would have been 0 G instead of 30 G.

In discussing the accepted view about the existence of dynamo action at the solar surface, we have gone a step further and suggested that the observed spatial distribution of quiet sun fields seems to be at odds with a granularly driven SSD. The argument used to make this claim was that in such a dynamo, all the magnetic byproducts must necessarily have a uniform spatial distribution at scales above that of a granule. We have found, however, that there are voids of magnetic activity (dead calm areas) in, both, the average apparent longitudinal and transverse fluxes of deep magnetograms and in the distribution of emerging loops. In fact, we have translated the loop emergence rate found by Martínez González et al. (2012) into a rate of 1 loop per 6 granules which can also be thought of as 1 emerging loop per mesogranule. It is clear that mesogranulation scales are very relevant for the quiet sun fields. SSD simulations including them are needed to see if they explain the presence of these voids in magnetic activity and emerging loop frequency. Given the fact that as we go deeper into the Sun, one reaches higher $\mathrm{R}e_m$ and P_m values, it is very tempting to suggest that SSDs acting in a range of convective scales larger than the granular ones are those that give rise to the presently observed internetwork fields. Note that in his work, Cattaneo (1999) already mentioned larger scales, such as those of the supergranulation, as possible places where to host dynamo activity. This might still be compatible with an SSD at granular scales that generates fields much weaker and that have not yet been observed by any of our currently available diagnostic techniques.

We have also suggested that the internetwork fields revealed by Hinode/SP and those that generate the Hanle depolarization of some atomic lines might have a lot more in common than previously thought (see however Lites et al. 2009; Bellot Rubio and Orozco Suárez 2012). The reason for this identification is based on the results from Orozco Suárez and Bellot Rubio (2012) and Bellot Rubio and Orozco Suárez (2012) who have shown that the quiet sun fields share the same field strengths, inclinations and azimuths than those needed by the fields detected with the Hanle effect. This is, of course, compatible with a continuous spectrum of fields in which the ranges corresponding to the two types of fields (the internetwork and the 'hidden' Hanle fields) simply overlap over a much larger fraction than thought so far. Of course, the internetwork fields will also include a fraction of vertical kG fields that contributes nothing to the Hanle depolarization and the weak granular fields that depolarize the light in molecular lines never make an imprint in the FeI Zeeman lines observed by Hinode/SP at current sensitivities. But, of this continuous distribution of fields, the range of hG strengths with largely transverse orientations and spatially organized at granular scales, contributes simultaneously to, both, the Zemman and the Hanle observations. If this result is confirmed (as, e.g., with the SIR inversions and the Hanle computations mentioned in Section 3) an important step to clarify the currently complex debate of the nature of the quiet sun magnetism would be achieved. We also want to stress that the evidence that the internetwork field component is composed of largely transverse fields renders the debate about the mean value of $<|B_L^{app}|>$ (or of $<|B_L|>$ for that matter) obsolete. Stokes V (longitudinal) magnetograms of the internetwork simply show a rather incomplete picture of these fields.

Note that many of the results commented above have benefited from high polarimetric sensitivities. Hanle measurements have always been very demanding in

polarimetric accuracy. The deep magnetograms of SUNRISE/IMaX and the long integrations with Hinode/SP used by Orozco Suárez and Bellot Rubio (2012) both were at the 10^{-4} polarimetric sensitivity. This is not a coincidence. Much of the future progress will be achieved with sensitivities in this range. Those more regularly reached in present day observations, 10^{-3}, are due to instrumental limitations that have nothing to do with physical processes in the Sun. Polarimeters observing the solar photosphere with sensitivities of 10^{-4} and sub-arcsecond resolutions using the Zeeman and the Hanle effects will consolidate (or refute) many of the aspects commented here. The need for high spatial resolution observations of the SrI depolarization cannot be emphasized enough (Stenflo 2012). These targets demand large apertures similar to those planned for future facilities such as the 4m class ground-based telescopes (ATST, EST Keil et al. 2011; Collados et al. 2010) and the Japanese led Solar-C mission (1.5m aperture). All these facilities will likely have to be used outside of the diffraction limit to pursue high sensitivity spectropolarimetry thanks to their large collecting areas Keller (1999).

Finally, observing regions of the Sun hardly reachable from the ecliptic will also help to clarify the nature of the quiet sun magnetism. The ESA-led Solar Orbiter mission (Müller et al. 2012) will carry on-board a magnetograph (the Polarimetric and Helioseismic Imager, PHI; Gandorfer et al. 2011) similar to that of SDO/HMI (Scherrer et al. 2012) and will observe the dynamics of the solar poles from an inclination of 35^o with respect to the solar equator. Observing the poles is crucial in this discussion because they represent the regions at farther distances from the activity belts in the Sun. In the absence of an SSD mechanism working at the solar surface, the origin of the internetwork fields can only be explained as a result of the cascading down towards the smallest scales (see the discussion in Schüssler and Vögler 2008) of the global dynamo fields. This effect is inevitably present on the Sun, but whether it affects only to network fields or to internetwork ones can best be discerned by observing their latitudinal properties with good spatial resolution and sensitivity.

Acknowledgements This work has been partially funded by the Spanish MINECO through Project No. AYA200AYA2011-29833-C06. Comments on an original version of the manuscript by D. Orozco, K. Petrovay and an unknown referee are gratefully acknowledged. ISSI support to attend the meeting is also acknowledged.

References

W.P. Abbett, The Magnetic Connection between the Convection Zone and Corona in the Quiet Sun. Astrophys. J. **665**, 1469–1488 (2007)

A. Asensio Ramos, Evidence for Quasi-Isotropic Magnetic Fields from Hinode Quiet-Sun Observations. Astrophys. J. **701**, 1032–1043 (2009)

G.K. Batchelor, On the Spontaneous Magnetic Field in a Conducting Liquid in Turbulent Motion. Royal Society of London Proceedings Series A **201**, 405–416 (1950)

L.R. Bellot Rubio, D. Orozco Suárez, Pervasive Linear Polarization Signals in the Quiet Sun. Astrophys. J. **757**, 19 (2012)

S. Boldyrev, F. Cattaneo, Magnetic-Field Generation in Kolmogorov Turbulence. Physical Review Letters **92**(14), 144501 (2004)

J.M. Borrero, P. Kobel, Inferring the magnetic field vector in the quiet Sun. I. Photon noise and selection criteria. Astron. Astrophys. **527**, 29 (2011)

A. Brandenburg, Nonlinear Small-scale Dynamos at Low Magnetic Prandtl Numbers. Astrophys. J. **741**, 92 (2011)

F. Cattaneo, On the Origin of Magnetic Fields in the Quiet Photosphere. Astrophys. J. Letters **515**, 39–42 (1999)

R. Centeno, H. Socas-Navarro, B. Lites, M. Kubo, Z. Frank, R. Shine, T. Tarbell, A. Title, K. Ichimoto, S. Tsuneta, Y. Katsukawa, Y. Suematsu, T. Shimizu, S. Nagata, Emergence of Small-Scale Magnetic Loops in the Quiet-Sun Internetwork. Astrophys. J. Letters **666**, 137–140 (2007)

M. Collados, F. Bettonvil, L. Cavaller, I. Ermolli, B. Gelly, A. Pérez, H. Socas-Navarro, D. Soltau, R. Volkmer, EST Team, European Solar Telescope: Progress status. Astronomische Nachrichten **331**, 615 (2010)

S. Danilovic, M. Schüssler, S.K. Solanki, Probing quiet Sun magnetism using MURaM simulations and Hinode/SP results: support for a local dynamo. Astron. Astrophys. **513**, 1 (2010a)

S. Danilovic, B. Beeck, A. Pietarila, M. Schüssler, S.K. Solanki, V. Martínez Pillet, J.A. Bonet, J.C. del Toro Iniesta, V. Domingo, P. Barthol, T. Berkefeld, A. Gandorfer, M. Knölker, W. Schmidt, A.M. Title, Transverse Component of the Magnetic Field in the Solar Photosphere Observed by SUNRISE. Astrophys. J. Letters **723**, 149–153 (2010b)

A.G. de Wijn, J.O. Stenflo, S.K. Solanki, S. Tsuneta, Small-Scale Solar Magnetic Fields. Space Science Reviews **144**, 275–315 (2009)

A. Gandorfer, S.K. Solanki, J. Woch, V. Martínez Pillet, A. Álvarez Herrero, T. Appourchaux, The Solar Orbiter Mission and its Polarimetric and Helioseismic Imager (SO/PHI). Journal of Physics Conference Series **271**(1), 012086 (2011)

P. Gömöry, C. Beck, H. Balthasar, J. Rybák, A. Kučera, J. Koza, H. Wöhl, Magnetic loop emergence within a granule. Astron. Astrophys. **511**, 14 (2010)

S.L. Guglielmino, V. Martínez Pillet, J.A. Bonet, J.C. del Toro Iniesta, L.R. Bellot Rubio, S.K. Solanki, W. Schmidt, A. Gandorfer, P. Barthol, M. Knölker, The Frontier between Small-scale Bipoles and Ephemeral Regions in the Solar Photosphere: Emergence and Decay of an Intermediate-scale Bipole Observed with SUNRISE/IMaX. Astrophys. J. **745**, 160 (2012)

H.J. Hagenaar, C.J. Schrijver, A.M. Title, The Properties of Small Magnetic Regions on the Solar Surface and the Implications for the Solar Dynamo(s). Astrophys. J. **584**, 1107–1119 (2003)

J.W. Harvey, D. Branston, C.J. Henney, C.U. Keller, SOLIS and GONG Teams, Seething Horizontal Magnetic Fields in the Quiet Solar Photosphere. Astrophys. J. Letters **659**, 177–180 (2007)

R. Ishikawa, S. Tsuneta, The Relationship between Vertical and Horizontal Magnetic Fields in the Quiet Sun. Astrophys. J. **735**, 74 (2011)

R. Ishikawa, S. Tsuneta, J. Jurčák, Three-Dimensional View of Transient Horizontal Magnetic Fields in the Photosphere. Astrophys. J. **713**, 1310–1321 (2010)

A.B. Iskakov, A.A. Schekochihin, S.C. Cowley, J.C. McWilliams, M.R.E. Proctor, Numerical Demonstration of Fluctuation Dynamo at Low Magnetic Prandtl Numbers. Physical Review Letters **98**(20), 208501 (2007)

S.L. Keil, T.R. Rimmele, J. Wagner, D. Elmore, ATST Team, ATST: The Largest Polarimeter, in *Solar Polarization 6*, ed. by J.R. Kuhn, D.M. Harrington, H. Lin, S.V. Berdyugina, J. Trujillo-Bueno, S.L. Keil, T. Rimmele Astronomical Society of the Pacific Conference Series, vol. 437, 2011, p. 319

C. Keller, The Advanced Solar Telescope: I. Science Goals, in *High Resolution Solar Physics: Theory, Observations, and Techniques*, ed. by T.R. Rimmele, K.S. Balasubramaniam, R.R. Radick Astronomical Society of the Pacific Conference Series, vol. 183, 1999, p. 169

C.U. Keller, F.-L. Deubner, U. Egger, B. Fleck, H.P. Povel, On the strength of solar intra-network fields. Astron. Astrophys. **286**, 626–634 (1994)

L. Kleint, A.I. Shapiro, S.V. Berdyugina, M. Bianda, Solar turbulent magnetic fields: Non-LTE modeling of the Hanle effect in the C_2 molecule. Astron. Astrophys. **536**, 47 (2011)

T. Kosugi, K. Matsuzaki, T. Sakao, T. Shimizu, Y. Sone, S. Tachikawa, T. Hashimoto, K. Minesugi, A. Ohnishi, T. Yamada, S. Tsuneta, H. Hara, K. Ichimoto, Y. Suematsu, M. Shimojo, T. Watanabe, S. Shimada, J.M. Davis, L.D. Hill, J.K. Owens, A.M. Title, J.L. Culhane, L.K. Harra, G.A. Doschek, L. Golub, The Hinode (Solar-B) Mission: An Overview. Solar Phys. **243**, 3–17 (2007)

H. Lin, On the Distribution of the Solar Magnetic Fields. Astrophys. J. **446**, 421 (1995)

B.W. Lites, Hinode Observations Suggesting the Presence of a Local Small-scale Turbulent Dynamo. Astrophys. J. **737**, 52 (2011)

B.W. Lites, *et al.*, The Horizontal Magnetic Flux of the Quiet-Sun Internetwork as Observed with the Hinode Spectro-Polarimeter. Astrophys. J. **672**, 1237–1253 (2008)
B.W. Lites, K.D. Leka, A. Skumanich, V. Martinez Pillet, T. Shimizu, Small-Scale Horizontal Magnetic Fields in the Solar Photosphere. Astrophys. J. **460**, 1019 (1996)
B.W. Lites, M. Kubo, H. Socas-Navarro, T. Berger, Z. Frank, R. Shine, T. Tarbell, A.M. Title, K. Ichimoto, Y. Katsukawa, S. Tsuneta, Y. Suematsu, T. Shimizu, S. Nagata, Has Hinode Revealed the Missing Turbulent Flux of the Quiet Sun?, in *Solar Polarization 5: In Honor of Jan Stenflo*, ed. by S.V. Berdyugina, K.N. Nagendra, R. Ramelli Astronomical Society of the Pacific Conference Series, vol. 405, 2009, p. 173
M.J. Martínez González, L.R. Bellot Rubio, Emergence of Small-scale Magnetic Loops Through the Quiet Solar Atmosphere. Astrophys. J. **700**, 1391–1403 (2009)
M.J. Martínez González, R. Manso Sainz, A. Asensio Ramos, E. Hijano, Dead Calm Areas in the Very Quiet Sun. Astrophys. J. **755**, 175 (2012)
V. Martínez Pillet, J.C. Del Toro Iniesta, A. Álvarez-Herrero, V. Domingo, J.A. Bonet, L. González Fernández, A. López Jiménez, C. Pastor, J.L. Gasent Blesa, P. Mellado, J. Piqueras, B. Aparicio, M. Balaguer, E. Ballesteros, T. Belenguer, L.R. Bellot Rubio, T. Berkefeld, M. Collados, W. Deutsch, A. Feller, F. Girela, B. Grauf, R.L. Heredero, M. Herranz, J.M. Jerónimo, H. Laguna, R. Meller, M. Menéndez, R. Morales, D. Orozco Suárez, G. Ramos, M. Reina, J.L. Ramos, P. Rodríguez, A. Sánchez, N. Uribe-Patarroyo, P. Barthol, A. Gandorfer, M. Knoelker, W. Schmidt, S.K. Solanki, S. Vargas Domínguez, The Imaging Magnetograph eXperiment (IMaX) for the Sunrise Balloon-Borne Solar Observatory. Solar Phys. **268**, 57–102 (2011)
N. Meunier, R. Tkaczuk, T. Roudier, M. Rieutord, Velocities and divergences as a function of supergranule size. Astron. Astrophys. **461**, 1141–1147 (2007)
R. Moll, J. Pietarila Graham, J. Pratt, R.H. Cameron, W.-C. Müller, M. Schüssler, Universality of the Small-scale Dynamo Mechanism. Astrophys. J. **736**, 36 (2011)
D. Müller, R.G. Marsden, O.C. St. Cyr, H.R. Gilbert, Solar Orbiter. Solar Phys., 193 (2012)
A. Nordlund, A. Brandenburg, R.L. Jennings, M. Rieutord, J. Ruokolainen, R.F. Stein, I. Tuominen, Dynamo action in stratified convection with overshoot. Astrophys. J. **392**, 647–652 (1992)
D. Orozco Suárez, L.R. Bellot Rubio, Analysis of Quiet-Sun Internetwork Magnetic Fields Based on Linear Polarization Signals. Astrophys. J. **751**, 2 (2012)
D. Orozco Suárez, L.R. Bellot Rubio, J.C. del Toro Iniesta, S. Tsuneta, B.W. Lites, K. Ichimoto, Y. Katsukawa, S. Nagata, T. Shimizu, R.A. Shine, Y. Suematsu, T.D. Tarbell, A.M. Title, Quiet-Sun Internetwork Magnetic Fields from the Inversion of Hinode Measurements. Astrophys. J. Letters **670**, 61–64 (2007)
K. Petrovay, G. Szakaly, The origin of intranetwork fields: a small-scale solar dynamo. Astron. Astrophys. **274**, 543 (1993)
J. Pietarila Graham, R. Cameron, M. Schüssler, Turbulent Small-Scale Dynamo Action in Solar Surface Simulations. Astrophys. J. **714**, 1606–1616 (2010)
J. Pietarila Graham, S. Danilovic, M. Schüssler, The Small-scale Solar Surface Dynamo (keynote), in *The Second Hinode Science Meeting: Beyond Discovery-Toward Understanding*, ed. by B. Lites, M. Cheung, T. Magara, J. Mariska, K. Reeves Astronomical Society of the Pacific Conference Series, vol. 415, 2009a, p. 43
J. Pietarila Graham, S. Danilovic, M. Schüssler, Turbulent Magnetic Fields in the Quiet Sun: Implications of Hinode Observations and Small-Scale Dynamo Simulations. Astrophys. J. **693**, 1728–1735 (2009b)
B. Ruiz Cobo, J.C. del Toro Iniesta, Inversion of Stokes profiles. Astrophys. J. **398**, 375–385 (1992)
J. Sánchez Almeida, On the Sr I λ4607 Å Hanle depolarization signals in the quiet Sun. Astron. Astrophys. **438**, 727–732 (2005)
J. Sánchez Almeida, M. Martínez González, The Magnetic Fields of the Quiet Sun, in *Solar Polarization 6*, ed. by J.R. Kuhn, D.M. Harrington, H. Lin, S.V. Berdyugina, J. Trujillo-Bueno, S.L. Keil, T. Rimmele Astronomical Society of the Pacific Conference Series, vol. 437, 2011, p. 451
J. Sánchez Almeida, T. Emonet, F. Cattaneo, Polarization of Photospheric Lines from Turbulent Dynamo Simulations. Astrophys. J. **585**, 536–552 (2003)
A.A. Schekochihin, S.C. Cowley, J.L. Maron, J.C. McWilliams, Critical Magnetic Prandtl Number for Small-Scale Dynamo. Physical Review Letters **92**(5), 054502 (2004a)
A.A. Schekochihin, S.C. Cowley, S.F. Taylor, J.L. Maron, J.C. McWilliams, Simulations of the

Small-Scale Turbulent Dynamo. Astrophys. J. **612**, 276–307 (2004b)

A.A. Schekochihin, N.E.L. Haugen, A. Brandenburg, S.C. Cowley, J.L. Maron, J.C. McWilliams, The Onset of a Small-Scale Turbulent Dynamo at Low Magnetic Prandtl Numbers. Astrophys. J. Letters **625**, 115–118 (2005)

A.A. Schekochihin, A.B. Iskakov, S.C. Cowley, J.C. McWilliams, M.R.E. Proctor, T.A. Yousef, Fluctuation dynamo and turbulent induction at low magnetic Prandtl numbers. New Journal of Physics **9**, 300 (2007)

P.H. Scherrer, J. Schou, R.I. Bush, A.G. Kosovichev, R.S. Bogart, J.T. Hoeksema, Y. Liu, T.L. Duvall, J. Zhao, A.M. Title, C.J. Schrijver, T.D. Tarbell, S. Tomczyk, The Helioseismic and Magnetic Imager (HMI) Investigation for the Solar Dynamics Observatory (SDO). Solar Phys. **275**, 207–227 (2012)

M. Schüssler, A. Vögler, Strong horizontal photospheric magnetic field in a surface dynamo simulation. Astron. Astrophys. **481**, 5–8 (2008)

N. Shchukina, J. Trujillo Bueno, Determining the Magnetization of the Quiet Sun Photosphere from the Hanle Effect and Surface Dynamo Simulations. Astrophys. J. Letters **731**, 21 (2011)

S.K. Solanki, Photospheric Magnetic Field: Quiet Sun, in *Solar Polarization 5: In Honor of Jan Stenflo*, ed. by S.V. Berdyugina, K.N. Nagendra, R. Ramelli Astronomical Society of the Pacific Conference Series, vol. 405, 2009, p. 135

S.K. Solanki, P. Barthol, S. Danilovic, A. Feller, A. Gandorfer, J. Hirzberger, T.L. Riethmüller, M. Schüssler, J.A. Bonet, V. Martínez Pillet, J.C. del Toro Iniesta, V. Domingo, J. Palacios, M. Knölker, N. Bello González, T. Berkefeld, M. Franz, W. Schmidt, A.M. Title, SUNRISE: Instrument, Mission, Data, and First Results. Astrophys. J. Letters **723**, 127–133 (2010)

H.C. Spruit, A model of the solar convection zone. Solar Phys. **34**, 277–290 (1974)

R.F. Stein, Solar Surface Magneto-Convection. Living Reviews in Solar Physics **9**, 4 (2012)

R.F. Stein, Å. Nordlund, Solar Small-Scale Magnetoconvection. Astrophys. J. **642**, 1246–1255 (2006)

R.F. Stein, D. Bercik, Å. Nordlund, Solar Surface Magneto-convection, in *Current Theoretical Models and Future High Resolution Solar Observations: Preparing for ATST*, ed. by A.A. Pevtsov, H. Uitenbroek Astronomical Society of the Pacific Conference Series, vol. 286, 2003, p. 121

O. Steiner, R. Rezaei, Recent Advances in the Exploration of the Small-scale Structure of the Quiet Solar Atmosphere: Vortex Flows, the Horizontal Magnetic Field, and the Stokes- V Line-ratio Method, in *Fifth Hinode Science Meeting*, ed. by L. Golub, I. De Moortel, T. Shimizu Astronomical Society of the Pacific Conference Series, vol. 456, 2012, p. 3

O. Steiner, R. Rezaei, W. Schaffenberger, S. Wedemeyer-Böhm, The Horizontal Internetwork Magnetic Field: Numerical Simulations in Comparison to Observations with Hinode. Astrophys. J. Letters **680**, 85–88 (2008)

J.O. Stenflo, The Hanle effect and the diagnostics of turbulent magnetic fields in the solar atmosphere. Solar Phys. **80**, 209–226 (1982)

J.O. Stenflo, Unsolved Problems in Solar Polarization, in *Solar Polarization 6*, ed. by J.R. Kuhn, D.M. Harrington, H. Lin, S.V. Berdyugina, J. Trujillo-Bueno, S.L. Keil, T. Rimmele Astronomical Society of the Pacific Conference Series, vol. 437, 2011, p. 3

J.O. Stenflo, Basal magnetic flux and the local solar dynamo. ArXiv e-prints (2012)

A.M. Title, T.D. Tarbell, K.P. Topka, S.H. Ferguson, R.A. Shine, SOUP Team, Statistical properties of solar granulation derived from the SOUP instrument on Spacelab 2. Astrophys. J. **336**, 475–494 (1989)

J. Trujillo Bueno, Modeling Scattering Polarization for Probing Solar Magnetism, in *Solar Polarization 6*, ed. by J.R. Kuhn, D.M. Harrington, H. Lin, S.V. Berdyugina, J. Trujillo-Bueno, S.L. Keil, T. Rimmele Astronomical Society of the Pacific Conference Series, vol. 437, 2011, p. 83

J. Trujillo Bueno, A. Asensio Ramos, N. Shchukina, The Hanle Effect in Atomic and Molecular Lines: A New Look at the Sun's Hidden Magnetism, in *Astronomical Society of the Pacific Conference Series*, ed. by R. Casini, B.W. Lites Astronomical Society of the Pacific Conference Series, vol. 358, 2006, p. 269

J. Trujillo Bueno, N. Shchukina, A. Asensio Ramos, A substantial amount of hidden magnetic energy in the quiet Sun. Nature **430**, 326–329 (2004)

S. Tsuneta, K. Ichimoto, Y. Katsukawa, S. Nagata, M. Otsubo, T. Shimizu, Y. Suematsu, M. Nakagiri, M. Noguchi, T. Tarbell, A. Title, R. Shine, W. Rosenberg, C. Hoffmann, B. Jurcevich, G. Kushner, M. Levay, B. Lites, D. Elmore, T. Matsushita, N. Kawaguchi,

H. Saito, I. Mikami, L.D. Hill, J.K. Owens, The Solar Optical Telescope for the Hinode Mission: An Overview. Solar Phys. **249**, 167–196 (2008)
B. Viticchié, On the Polarimetric Signature of Emerging Magnetic Loops in the Quiet Sun. Astrophys. J. Letters **747**, 36 (2012)
A. Vögler, M. Schüssler, A solar surface dynamo. Astron. Astrophys. **465**, 43–46 (2007)
C. Westendorp Plaza, J.C. del Toro Iniesta, B. Ruiz Cobo, V. Martinez Pillet, B.W. Lites, A. Skumanich, Optical Tomography of a Sunspot. I. Comparison between Two Inversion Techniques. Astrophys. J. **494**, 453 (1998)
L. Yelles Chaouche, F. Moreno-Insertis, V. Martínez Pillet, T. Wiegelmann, J.A. Bonet, M. Knölker, L.R. Bellot Rubio, J.C. del Toro Iniesta, P. Barthol, A. Gandorfer, W. Schmidt, S.K. Solanki, Mesogranulation and the Solar Surface Magnetic Field Distribution. Astrophys. J. **727**, 30 (2011)